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FOR

OPTICAL ISOLATOR, ATTENUATOR AND POLARIZER SYSTEM AND METHOD FOR INTEGRATED OPTICS

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OPTICAL ISOLATOR, ATTENUATOR AND POLARIZER SYSTEM AND METHOD FOR INTEGRATED OPTICS

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to optics, and more particularly to optical isolators.

BACKGROUND OF THE INVENTION

An optical isolator is a 1x1 unidirectional connector. It allows light to travel along a path in one direction only but not in the reverse direction within an optical system.

Optical isolators are typically employed in bulk optical systems to eliminate one of two counter-propagating electro-magnetic light waves. An optical isolator is comparable with a diode having a low electrical resistance for the forward current from its input to its output and a very high resistance for the reverse current from its output to its input. Analogous, a forward light wave, fed via the optical input port of an optical isolator to its output port, is guided with low loss, and a reverse light wave, i.e. a light wave being fed to the isolator's optical output port, is attenuated such that only a very small amount thereof leaves the isolator via its input port. Such an optical isolator has a unidirectional transmittance property, and cuts off most of the light fed back into its output port.

The "non-reciprocity principle" may be applied to such optical devices to achieve the required isolation. The non-reciprocity principle refers to the fact that an optical signal transmits only in the forward direction but not in reverse. An ideal optical isolator is based on this non-reciprocity principle.

A Faraday rotator is one prior art optical isolator, which employs a magnetic-optic element as a non-reciprocal component. Unfortunately, such prior art optical isolator exhibits many difficulties. Not only is its function polarization dependent, but it is also difficult to be integrated with other optical devices.

DISCLOSURE OF THE INVENTION

An optical system and associated method are provided. Included is a first branch capable of allowing light to pass therethrough in a forward direction and a reverse direction. The first branch includes a first medium with a first refractive index (n_1), and a first end and a second end. Also included is a second branch capable of allowing light to pass therethrough in the forward direction. The second branch includes a second medium with a second refractive index (n_2, with $n_2 < n_1$), and a first end and a second end. The second end of the second branch is further coupled to the first branch to form an angle (ϑ_2). In use, $\vartheta_1 \geq \sin^{-1} (n_2 / n_1)$ to utilize the total reflection principle to prevent the light passing through the first branch in the reverse direction from passing into the second branch, where ϑ_1 is the incident angle of the light passing in the reverse direction from the first branch to the second branch.

In some embodiments, the first branch and the second branch may be components of a Y-junction, a K-junction, and/or an X-junction.

As an option, the first branch may include an optical absorber for absorbing the reverse light that is prevented from passing into the second branch by the total reflection. In another embodiment, an optical choker may be positioned at one of the ends of one of the branches for increasing isolation.

In use, the isolation provided between the first branch and the second branch is polarization independent. As an option, a numerical aperture of one of the ends of one of the branches may be lowered for increasing the isolation. Moreover, a transmitting area of one of the branches may be decreased for increasing the isolation. Still yet, an

optical choker may be positioned at one of the ends of one of the branches for increasing the isolation.

In various embodiments, the optical system may function as an optical isolator and/or an optical attenuator. Optionally, both the first branch and the second branch may have a substantially rectangular cross-section.

Still yet, the first branch and the second branch may be components of a first optical isolator. Optionally, a wavelength selector may be coupled to the optical isolator to form a de-multiplexer.

Further, a second optical isolator may be integrated with the first optical isolator. Thus, an optical coupler may be formed. When the optical coupler is formed, such may optionally function as an add-multiplexer, an optical inserter or a polarization beam combiner. Moreover, the optical coupler may include a Y-splitter.

In another embodiment, the first optical isolator and the second optical isolator may be integrated with a third optical isolator to form an optical circulator with 3 ports. In the same manner, an N-port optical circulator can be built. An optional wavelength selector may also be coupled to the circulator to form a de-multiplexer.

Each of the foregoing embodiments may be made of a very simple structure and have numerous optional features: ruggedness, superb thermal and environmental properties, premium stability and reliability, and excellent optical performance that are independent of polarization. Moreover, they may be easily integrated with other optical and opto-electronic devices. Each of them may be built with one or a combination of the waveguide, optical fiber, micro-optic, and photonic crystal technologies.

Moreover, the optical system may be designed to function as a polarizer.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1a, 1b, 1c, 1d, 1e, 1f, 1g and **1h** each show an optical isolator/attenuator of one embodiment.

Figs. 1i and **1j** show a modified output port of **Figs. 1a** and **1b.**

Figs. 2a and **2b** show the optical coupler/inserter/add-multiplexer/polarization beam combiner of one embodiment.

Fig. 3 represents an optical circulator of one embodiment.

Fig. 4 exhibits a 2x2 optical coupler with isolation among its inputs and outputs.

Fig. 5 depicts an optical polarizer of one embodiment.

Figs. 6a and **6b** illustrate an optical de-multiplexer of one embodiment.

Fig. 7 displays the magnified Y-junction of branches **14** and **15** in **Fig. 1a**.

Fig. 8 illustrates an optical choker of one embodiment.

Description of the Preferred Embodiments

Figs. 1a, 1b, 1c, 1d, 1e, 1f, 1g and **1h** each show an optical isolator/attenuator of one embodiment. Specially, each optical isolator/attenuator represents an optical device with a pair of ends. In the context of the present description, such ends may be any termination or intermediate reference points. For example, such ends may include an input port **18** and an output port **19**.

Optical isolators **301a, 301c** and **301e** of **Figs. 1a, 1c** and **1e**, respectively, comprise a Y-junction coupler made from two branches **14** and **15** of different refraction indices. In the context of the present description, a branch may refer to any medium capable of allowing light to pass therethrough.

Optical isolators **301b, 301d, 301f** of **Figs. 1b, 1d** and **1f**, respectively, comprise a K-junction. Moreover, optical isolators **301g, 301h** of **Figs. 1g** and **1h**, respectively, comprise an X-Junction. Then an extra port (i.e. port **21**) is available for monitoring output (i.e. port **19**) as well as for feedback control of these optical isolators.

At the Y-junction of the optical isolators **301a, 301c, 301e** (or K-or X-Junction in the other figures), the refraction index (n_1) of the branch **15** is greater than that (n_2) of the branch **14**. An optical unidirectional Y-junction (K- or X- Junction) coupler may then be constructed using the total reflection principle. This ensures that light travels only in the forward direction. Incoming light from port **18** travels through branch **14**, reaches branch **15** and through it to exit port **19**. And for the reverse direction, light entering from port **19** passes through branch **15**, meets branch **14** with incident angle ϑ_1 (cf. Fig. 7), but is blocked by the total reflection phenomenon because the condition of $\vartheta_1 \geq \sin^{-1} (n_2 / n_1)$ is met. Thus, light cannot get into branch **14** but stays in branch **15**. In the end,

it either exits from port **22** or is consumed by an optional absorber **17**. The following examples are estimations made based on the plane wave approximation:

Example 1

Case 1)

For **Figs. 1a** and **1b**: given the refraction indexes $n_1 = 1.465$, $n_2 = 1.460$, $n_3 = 1.455$ and $\vartheta_2 = 85.30°$, then the calculated insertion loss is ~0.13dB with ILp = 0.129dB and ILs = 0.133dB. The polarization dependent loss (i.e. ILs - ILp) is ~0.004dB and the isolation is ~9dB.

Case 2)

For **Figs. 1c** and **1d**: given the refractive indexes $n_1 = 1.465$, $n_{1c} = 1.460$, $n_2 = 1.4625$, $n_{2c} = 1.4575$ and $\vartheta_2 = 86.70°$, then the calculated insertion loss is ~0.13dB with ILp = 0.133dB and ILs = 0.136dB. The polarization dependent loss is ~0.003dB while the isolation is also ~9dB.

Thus, the isolation is polarization independent (ILp ≈ ILs). However, the isolation of ~9dB is below expectation. In Case 1 of Example 1 above, although with ideally parallel incident light, the numerical aperture of the output light $NA(n_1, n_3)$ is 0.171 at the output port **19** while the other numerical apertures are: $NA(n_2, n_3) = 0.121$, $NA(n_1, n_2) = 0.121$. Since $NA(n_1, n_3)$ is greater than $NA(n_1, n_2)$, a portion of the reverse light from Port **19** is able to get into port **18**. This is because the incident angle of some reverse light ϑ_1 (as in **Fig. 7**) is smaller than the total reflection critical angle ϑ_{1c}, causing the isolation to be low. The resultant isolation is dependent on the effectiveness of the total

reflection for the reverse light. The better the effectiveness of the total reflection for the reverse light, the higher the isolation.

One optional way to achieve higher isolation is to lower the numerical aperture of the output port **19**. Additional optical output ports **301i** and **301j** are illustrated by **Fig. 1i** and **1j** respectively. For the optical output port **301i**, calculations indicate that for 97% of the output light, the numerical aperture has dropped to 0.121 ($NA(n_2, n_3)$). For the other 3%, the numerical aperture is still 0.171 ($NA(n_1, n_3)$). Removing this 3% of output light decreases the NA to 0.121, but it increases the insertion loss by 0.13dB while the area of the output light is enlarged. For the optical output port **301j**, the optimal calculations generated essentially the same results but with an output area that is larger than that of **301i**. Although the output numerical aperture has been lowered, the isolation is not improved since the extra reverse light due to the enlarged area of port **19** is getting into port **18**.

One can use an X-Junction to lower the numerical aperture of the output port **19** (see, for example, **Fig. 1g**). The following examples are pertinent to the embodiment of **Fig. 1g**.

<u>Example 2</u>

For **Fig. 1g**: given the refraction indexes $n_1 = 1.500$, $n_{1c} = 1.4958$, $n_2 = 1.450$ $n_{2c} = 1.4457$, $\vartheta_2 = 85°$ and $\vartheta_1 = 76°$, the calculated insertion loss are ILp = 1.24dB and ILs = 1.39dB. The polarization dependent loss is ~0.15dB, the numerical aperture of the output port 19 is low and thus the isolation greatly increases to ~12dB.

Another way of improving isolation for **301a, 301b, 301c, 301d, 301e** and **301f** is to decrease the transmitting area of the reverse light from branch **15** to branch **14**. If it is

reduced to one half, the isolation increases by 3dB, and by 6dB if it is reduced to one fourth. And if all the reverse light were reflected at the junction of branches **15** and **14**, then the isolation becomes perfect. Therefore, one may add an optical choker **1** to port **18, 19,** as shown in **Figs. 1e, 1f** and **1h**. The optical choker **1** serves two purposes: (1) it lowers the numerical aperture NA, for example from 0.171 to 0.1 or even 0.01 (2) it converges the light to the center part of branches **14** and **15**. The resultant optical isolators **301e, 301f** and **301h** of **Figs. 1e, 1f** and **1h** have much better optical performance and still can be easily cascaded and integrated.

Optical isolators **301a, 301b, 301c, 301d, 301e, 301f, 301g** and **301h** may also function as an optical attenuator. Light coming in from port **18** exits from port **19** with a fixed amount of attenuation. See Example 3:

Example 3

> In the context of Example 1, if the input light numerical aperture NA was 0.12 and $\vartheta_2 = 85°$, the attenuation of both the p- and s-polarization are $\approx$ 4.3dB and their difference is almost zero (0.009dB).

Therefore, the attenuation is polarization independent. Calculations indicate that the smaller the angle ϑ_2, the larger the attenuation. The attenuation can be varied with the changing incident angle ϑ_2. Thus, a variable optical attenuator is also feasible.

Optical isolator **301a, 301b, 301c, 301d, 301e, 301f, 301g** and **301h,** based on the total reflection principle, have a very simple structure and result in numerous improvements: its ruggedness, its superior thermal and environmental properties, its exceptional stability and reliability, and its excellent polarization independent optical performance. Moreover, it is easily integrated with other optical and opto-electronic devices. These qualities make it

suitable to construct other optical devices such as a coupler, inserter, polarization beam combiner, circulator, add-multiplexer, and de-multiplexer.

To optimize the optical isolators **301a, 301b, 301c, 301d, 301e, 301f, 301g** and **301h,** the shape of the Y-, K- or X-Junction may be changed. Different refractive index n_1 and n_2 of branches **15** and **14** may be obtained (from different dielectric materials or the same dielectric material with different effective refractive index from tapered shape). The refractive index may not necessarily be constant, but rather be a function of position x, y, and z. The cross section of branches (waveguide or optical fibers, etc.) may, in one embodiment, be square or rectangular.

Thus, one embodiment is based on the non-reciprocal phenomenon of total reflection and can be polarization independent and ideally suited for integration. According to Snell's law of optical refraction, total reflection occurs when light propagates from an optically denser medium (with a higher refractive index n_1) into another less dense medium (with a lower refractive index n_2), and the incident angle ϑ_1 exceeds the critical value ϑ_{1C}, that is $\vartheta_1 \geq \vartheta_{1C} = \sin^{-1}(n_2 / n_1)$.

As a result, all the incident light is reflected back into the first medium, and the transmitted light is totally blocked. Since n_1 is greater than n_2, n_2 must not be greater than n_1. Thus, the total reflection is non-reciprocal and it occurs only when light travels from n_1 medium into n_2 medium, but never occurs for the reverse direction from n_2 medium into n_1 medium. Utilizing total reflection, one may build optical isolators **301a, 301b, 301c, 301d, 301e, 301f, 301g** and **301h**. Any combination of suitable branches could constitute as the optical transmission path and can be easily integrated with other opto-electronic devices (e.g. semiconductor devices).

Figs. 2a and **2b** represent an optical coupler **302a** and **302b** built by cascading a series of optical isolators **301e, 301f** and **301h** together (for simplification, the K- and X-Junction type and the optical chokers **1** are not shown). Lights from input ports **18, 20** travel to output port **19**. Shown are 2x1 couplers with isolation function. Optical coupler **302a** and **302b** may also be used as polarization beam combiner with isolation because of their polarization independent performance. Optical couplers **302a** and **302b** also work as add-multiplexer to add an extra channel of signal (λ_j) from port **20** to an existing channel of signals (λ_1,λ_2...) from input port **18** without interfering each other, and outputs all signals (λ_1,λ_2...λ_j) from port **19**. An Nx1 add-multiplexer may be built using the same approach. Moreover, optical couplers **302a** and **302b** also work as an optical inserter (with isolation) for an optical fiber amplifier device with the optical signal connected to port **18**, the pump laser connected to port **20**, and the output port **19** connected to a fiber amplifier (not shown).

Fig. 3 depicts an optical circulator **303** built with three optical isolators **301e, 301f,** and **301h** without absorbers (again for simplification, the K- and X-Junction type and the optical chokers **1** are not shown). Light entering at port **28** travels along and leaves at the next port **29**. In a similar manner, light from port **29** may exit port **30**, and so on. The circulator **303** is also polarization independent. Optical circulators with 4 or more ports can be built in the same way.

Fig. 4 shows a 2x2 optical coupler **304**. It comprises a 2x1 optical coupler **302a** (or **302b**) and a Y-splitter. Light coming from ports **18** and **20** travels to the output ports **19** and **21**. Shown is a 2x2 optical coupler with isolation among the input ports and output ports. In principle, an NxM optical coupler with isolation may even be built.

Fig. 5 illustrates a polarizer **305** with an input port **18**, an output port **19** and an optional absorber **17**. See Example 4:

Example 4

Given $n_l = 4.25$, $n_{lc} = 4.248$, $n_2 = 1.460$, $n_{2c} = 1.455$, $\vartheta_2 = 71.04°$, and $\vartheta_l = 19°$, the resulting attenuation of the p-polarization light is $A_p = 2.2 \times 10^{-9}$ dB whereas attenuation of the s-polarization is $A_s = 4.2$ dB at port **21**.

The attenuation is therefore very much polarization dependent. Input light from port **18** with intensity (p, s), where p is the intensity of p-polarization and s is the intensity of s-polarization respectively, travels through the branch **14** to reach the junction. On one hand, it refracts into branch **15** and continues on to exit port **21** with intensity (p, 0.38s). On the other hand, it reflects into branch **13** and continues on to output port **19** with intensity (0, 0.62s). Port **19** is the output port of the polarized light.

The insertion loss of the polarizer **305** is low at 2.07dB. Consequently, it does not have good isolation. But, an optical isolator **301a, 301b, 301c, 301d, 301e, 301f, 301g** and **301h** can be integrated to build a polarizer **305** with good isolation.

Fig. 6a exhibits a de-multiplexer **306a**. It consists of an isolator **301e (301f** or **301h)** but without the absorber **17**, and a wavelength selector **61**. The wavelength selector **61** may be a band pass filter or a Bragg Gratings (with fiber or waveguide technology). Light signals with wavelength (λ_1, λ_2, λ_3...) coming from input port **18** travel through the output port **19** to reach the wavelength selector **61**. Then, the selected wavelength (e.g. λ_1) is reflected and exits from port **22**. The other signals with wavelength (λ_2, λ_3...) are transmitted through the selector **61** without loss.

Similarly, **Fig. 6b** displays a de-multiplexer **306b**. It includes a circulator **303** and a wavelength selector **61**. Optionally, the add-multiplexers **302a** and **302b** and de-

multiplexers **306a** and **306b** can be cascaded together to construct an add-/drop-multiplexer (not shown).

Fig. 7 is a magnified Y-junction of branches **14** and **15** of the optical isolator **301a**. The incident ray of light **34** passes through the isolator **301a**. On its way, it is reflected $\mathbf{r_{21}}$ and refracted $\mathbf{t_{21}}$ at $\mathbf{B_0}$, again reflected $\mathbf{r_{13}}$ and refracted $\mathbf{t_{13}}$ at $\mathbf{C_1}$, and then again at $\mathbf{B_1}$, $\mathbf{C_2}$, $\mathbf{B_2}$, ... and so on according to the Fresnel's formulae. For the most intensity of the incident light **34** to pass from the branch **14** into the branch **15,** $2h\tan\vartheta_1 > d$ may be satisfied, where d and h are the width of branches **14** and **15** respectively. The transmission coefficient is $\mathbf{t_{ij}} = 2p_i/(p_i + p_j)$, the reflection coefficient is $\mathbf{r_{ij}} = (p_i - p_j)/(p_i + p_j)$ where $p_i = n_i/\cos\vartheta_i$ for the TM wave, $p_i = n_i\cos\vartheta_i$ for the TE wave and i, j = 1, 2, 3 for medium n_1, n_2, n_3. Then, the transmissivity of region **I** is $\mathbf{T} = p_3|t|^2/p_1$ where $t = t_{21}t_{13}/(1-r_{13}{}^2e^{i2\beta})$. The phase difference of the adjacent transmitted lights $\mathbf{E_1}$ and $\mathbf{E_2}$ is $2\beta = (4\pi h n_1\cos\vartheta_1)/\lambda_0$ where λ_0 is the light wavelength in vacuum. If $\vartheta_2 \geq \vartheta_{2c} = \sin^{-1}(n_3/n_2)$, internal total reflections occur at $\mathbf{C_1}$, $\mathbf{C_2}$ ...$\mathbf{B_1}$, $\mathbf{B_2}$ ... and p_3 becomes a pure imaginary number. Hence the time average of the transmissivity **T** is zero. Similarly, the time average of the reflectivity **R** ($\mathbf{R_1}$, $\mathbf{R_2}$, ...) is also zero with the exception of $\mathbf{R_0} = \mathbf{r_{21}}^2$. Since the energy flux of $\mathbf{R_0}$ can be very small and it almost always escapes into n_3 medium, it does not add to the reflection loss of the optical isolator.

Fig. 8 illustrates an optical choker **800** of one embodiment.

In another embodiment, a computer program operates on a set of input parameters and desired output parameters associated with an optical system under design. Given such inputs, the computer program calculates and simulates the optical system, optimizes it so the resultant outputs meet the desired conditions such as the power, isolation, insertion loss, polarization, polarization dependent loss, return loss, etc. Optionally, the

various concepts and equations set forth hereinabove may be incorporated into the computer program for being calculated accordingly.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of a preferred embodiment should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.